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To cite this article: JM López de Ipiña *et al* 2017 *J. Phys.: Conf. Ser.* **838** 012007

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Towards an optimal adaptation of exposure to NOAA assessment methodology in Multi-Source Industrial Scenarios (MSIS): the challenges and the decision-making process

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Abstract. It is expected a progressive increase of the industrial processes that manufacture of intermediate (iNEPs) and end products incorporating ENMs (eNEPs) to bring about improved properties. Therefore, the assessment of occupational exposure to airborne NOAA will migrate, from the simple and well-controlled exposure scenarios in research laboratories and ENMs production plants using innovative production technologies, to much more complex exposure scenarios located around processes of manufacture of eNEPs that, in many cases, will be modified conventional production processes. Here will be discussed some of the typical challenging situations in the process of risk assessment of inhalation exposure to NOAA in Multi-Source Industrial Scenarios (MSIS), from the basis of the lessons learned when confronted to those scenarios in the frame of some European and Spanish research projects.

1. Motivation and context

According to the “Project on Emerging Nanotechnologies” inventory [1] [2], there are currently about 1830 final nano-products on the market. Lux Research Inc. [3] estimated that sales of end products incorporating nanotechnology (end nano-enabled products, eNEPs) grew by 90% over the period 2012-2014, from \$850 billion to \$1.6 trillion. In the same period, sales of intermediary products incorporating nanotechnology (intermediate nano-enabled products, iNEPs) also grew by 170%, reaching around \$360 billion in 2014. The global value of manufactured nanomaterials (ENMs) between 2012 and 2014 increased 35% from 2012 to reach \$ 2.12 billion in 2014. As a result, total nanotechnology sales in 2014 would be close to \$2 trillion. Other projections by the same emerging technologies consulting firm [4] estimate that the global market for nanotechnology products will reach \$4.4 trillion in 2018. But sales of “*true nanotechnology products*” (the sum of ENMs and iENPs) only accounted for 18% of the global nanotechnology market in 2014. In this sense, it is clear that the value of these products manufactured with breakthrough processes is little relevant compared to consumer finished goods incorporating nanotechnology.

Although market estimates may vary substantially depending of the source consulted, all sources point to a relevant and sustained growth of the nanotechnology market in the coming years, but less optimistic than expected at the beginning of the global recession period. Research and Markets [5], expects the global nanotechnology market to grow at a CAGR of about 17.5% during 2016-2022.



These projections are consistent with the longitudinal evolution of nanotechnology that is reflected in the global increase of patents and scientific publications [6].

With respect to the potentially exposed workforce, some projections estimate between 2 and 6 million in 2015 and 2020 the number of workers involved in some domain of nanotechnology (800,000 and 2 million respectively in the United States) [7]. PEROSH [8] - based on these same estimates - amounts to a workforce in Europe of 400,000 workers in 2015.

All these data suggest in the short-medium term a progressive increase of the industrial processes that use ENMs, but mainly of those processes of manufacture of end products that incorporate ENMs to provide improved properties (eENPs). It is therefore expected that the problem of assessing occupational exposure to airborne NOAA will migrate, from the simple and well-controlled exposure scenarios in research laboratories and ENMs production plants using innovative production technologies, to much more complex exposure scenarios located around processes of manufacture of eENPs that, in many cases, will be modified conventional production processes. A significant increase in exposure scenarios related to the production of iNEPs is also expected, either using new production technologies or modifying existing ones (Table 1). A third relevant group of occupational exposure scenarios to consider in the life cycle of ENMs will be linked to the progressive increase in the professional use of all these products in the different industrial and service sectors.

Manufacturing process	Nanotechnology product		
	Engineered nanomaterial (ENM)	Intermediate nano-enabled product (iNEP)	End nano-enabled product (eNEP)
New	+	++	++
Existing		+	+++
<i>Example</i>	<i>MWCNT</i>	<i>MWCNT-based composite</i>	<i>Automotive component</i>

Table 1. The nanotechnology value chain and the potential increase in number of occupational exposure scenarios to airborne NOAA associated with existing and new manufacturing processes [(+) Relevant increase, (++) Very relevant increase, (+++) Highly relevant increase].

In this industrial context, the expected proliferation of Multi-Source Industrial Scenarios (MSIS) [9], characterized by spatially complex distributions of aerosol sources as well as for potential differences in dynamics due to the feasibility of multi-task configuration at a given time, will increase the complexity of the occupational risk assessment to airborne NOAA. In addition, in these real-life complex scenarios uncertainty can significantly increase, mainly due to the lack of an effective distinction of a dynamic background aerosol [9,10,11].

The assessment of risks related to airborne exposure to chemical agents at work by comparison with limit values, is a well-established process regulated by OHS European Directives (e.g. Directives 89/391/EC, 98/24/EC, 2004/37/EC) and national legislations transposing the previous ones. The availability of a suitable instrumentation, well-standardized procedures and regulated limit values, makes risk assessment a standardized routine tool in the practice of industrial hygiene. In addition, this methodology provides security and confidence in compliance with legislation, both for the employer, the worker and its representatives, as well as for the competent public administration responsible for regulation.

For airborne NOAA - chemical agents for all purposes-, the already enforced occupational regulatory framework should be also routinely applied to these particular situations by industrial hygienists. Despite the lack of regulated limit values, the use of recommended and benchmark values [12,13] allows the implementation of this methodology for the risk management of the exposure to airborne NOAA in companies. However, despite the significant research efforts in recent years – measurement strategies and new tiered approach [14,15,16,17,18,19], portable and personal instrumentation [12,20,21,22], proposed NRVs/OELs [12,13,23,24] - uncertainties in the risk

assessment to NOAA (inhalation) in complex scenarios still affect significantly the robustness of the results, thus limiting the wide application of existing methods and strategies by industrial hygienists.

Among the set of different metrics for the assessment of exposure to airborne NOAA, particle number concentration (PNC) is a simple and useful parameter for industrial hygienists, because its simplicity of measurement through direct-reading portable and personal instrumentation [12,25], as well as the availability of mature sampling procedures [14,17] and recommended reference values [13] for the comparison with measurements, then allowing a quantitative approach to the hygienic risk assessment. However main limitation of PNC is the lack of selectivity, so depending of the airborne NOAA assessed and the exposure scenario, it will be distinguishable from the background.

The use of PNC in the assessment of low-medium complexity exposure scenarios (e.g. research laboratories, ENMs manufacturing plants) following the well-established tiered approaches has been well demonstrated and documented [25,26,27,28,29,30,31,32,33]. However, the use of this metric in MSIS can lead to erroneous results in the assessment of exposure due to unforeseen influences of simultaneously running processes. In addition, as reviewed in [15] the choice of the instrument, if possible, determines the measurement strategy and the final accuracy of the data.

In this work some examples of typical challenging situations using PNC for risk assessment of occupational exposure to airborne NOAA will be presented, from the basis of the lessons learned when confronted to those complex industrial scenarios, in the frame of some European and Spanish research projects [24,34].

2. Results on PNC temporal records

Here are presented four cases, very common in MSIS, leading to disambiguation problems of the PNC temporal record: the dynamic evolution of the background signal, the spatial differences of this signal, the instrument choice and the correct equivalent dimension.

2.1 Temporal background signal masking the potential contribution of NOAA release from the raw series of PNC.

Figure 1 shows raw PNC signals captured in source (blue) and background (red) by a CPC TSI 3075 and a portable CPC TSI 3007, located at a distance of four meters from each other, inside a maintenance room (6 x 4 x 3 m), during the measurement of occupational exposure to nanoTiO₂ (nTiO₂) in two working tasks: 1) the central drilling of cylindrical nTiO₂ enabled steel tablets (task T3) and its subsequent packaging with aluminum paper in packs of five (task T4) (see section 3 in this paper) [9,34].

It is observed that the background signal is larger than the measured in source; the maximum amplitude of the background signal is around 42,000 particles/cm³. Both signals have the same shape and evolve in parallel with an offset of about 2,000-5,000 particles/cm³. Their amplitude is greater before starting the working tasks and none of them seems influenced by potential NOAA releases during tasks development (tasks 3 and 4).

Temporal background signal overrides the potential contribution of NOAA release during mechanical processing. In such a situation it is impossible to evaluate the occupational exposure to nTiO₂ using only PNC.

2.2 Significant disagreement between signals of the background aerosol (PNC) measured in two positions situated very close to each other.

In the reaction stage of a ENMs manufacturing plant by Flame Spray Pyrolysis (reactor closed), significant disagreements were also found between signals of the background aerosol (PNC) measured simultaneously with similar instrumentation (ELPI, ELPI+) in two positions situated close to each other (7 m) [35].

The two raw PNC signals presented different shapes with uncorrelated fluctuations and an offset between the crests of both signals greater than 50,000 particles/cm³. Before starting the manufacturing process the offset between the background aerosols measured in both positions was about 20,000

particles/cm³. This situation alerts on the value of the background selected to calculate the net-exposure or emission PNC by subtraction of the background PNC value of the raw measured PNC.

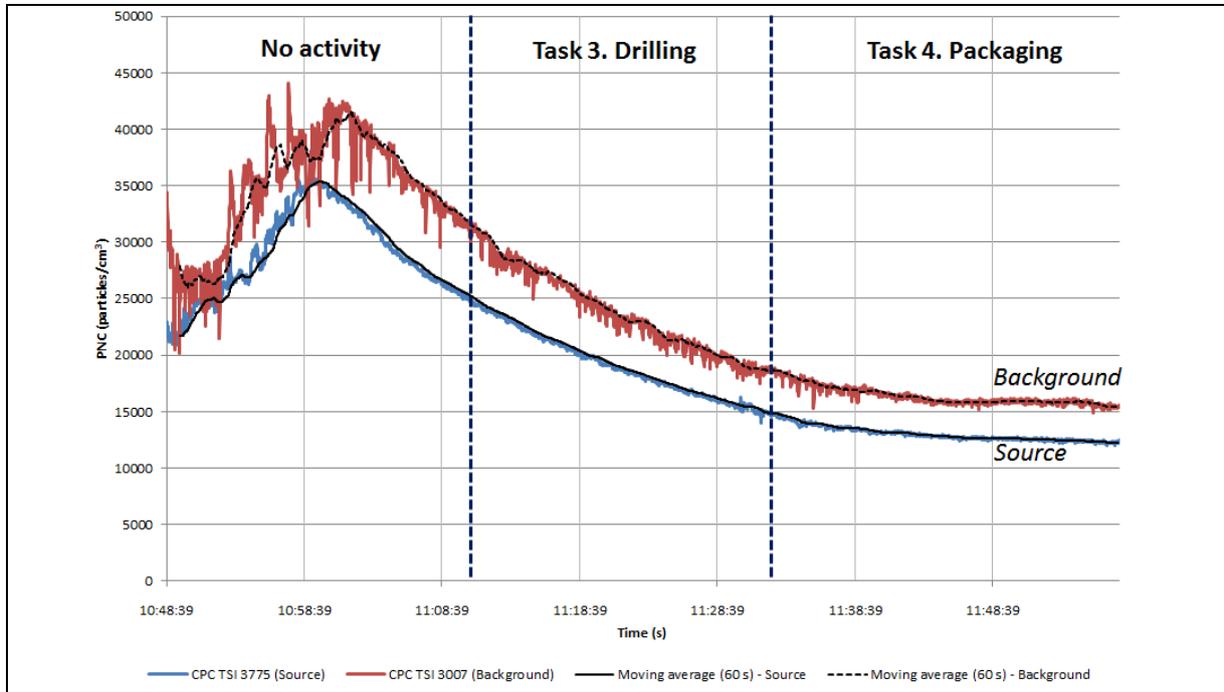


Figure 1. Temporal background signal masking the potential contribution of NOAA release from the raw series of PNC (See the explanation in the text).

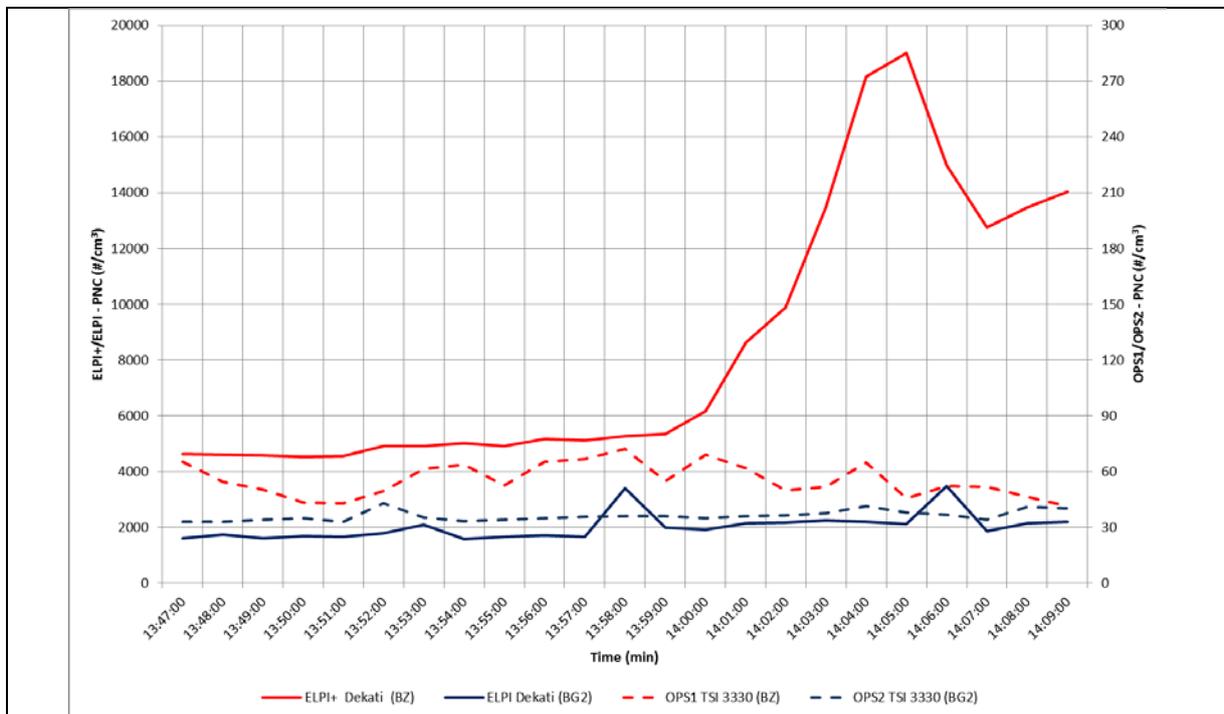


Figure 2. Discrepancies in PNC records from collocated instruments (See the explanation in the text).

2.3 Discrepancies in PNC records from collocated instruments. Instrument choice.

Figure 2, registered during the exposure assessment in a task of packaging nano-SiO₂ cans under an extraction hood, shows raw signals captured by four DRI, deployed in pairs (ELPI + OPS), in two measurement positions: the first one was located at the breathing zone of the worker (BZ) and the second one at a fixed point just 2 m from BZ (BG2). The four DRI operate in the following size ranges: ELPI (7 nm - 10 µm), ELPI+ (6 nm - 10 µm) and OPS1/2 (0.3 - 10 µm).

Analysis of PNC records revealed significant discrepancies between PNC measured at the BZ (in red) and at the fix position close to the BZ (in blue). At the same time, significant discrepancies were also observed among instrumentation measuring PNC at the BZ and sharing a common sampling point. For instance, the event observed by the ELPI+ at the BZ is neither observed by the collocated OPS nor at the close-background position (BG2).

This alerts on the importance of measuring worker exposures in the BZ, in accordance with the well-established industrial hygiene practices, for truly representative exposure measurements. The extrapolation of measured values at a fixed point close to the worker as if they were true values measured in the BZ can lead to significant errors in the assessment of the exposure to NOAA.

2.4 Aerosol characteristics retrieval (PNC) from simultaneously by measured metrics, such as aerodynamic and mobility equivalent diameters.

The analysis of the signals from a case study that deployed a multi-instrumental approach for the measurement of occupational exposure to nanoSiO₂ (ELPI +, CPC TSI 3007, SMPS NanoScan TSI 3910, CPC TSI 3775, NSAM TSI Aerotrak 9000, OPS TSI 3330, among others), showed that although the temporal evolution of the simultaneous signals captured in a fixed position by this instrumentation presented a satisfactory agreement and a similar shape, the signal offset between instruments using different measurement technologies and measurement windows (e.g. ELPI + - aerodynamic diameter and SMPS NanoScan TSI 3910 - mobility diameter) could exceed 50% of the measured value.

This alerts on the selection of the measuring technology and instrument used to provide the PNC exposure value.

3. Discussion: the decision making process

Pitfalls described in previous section can introduce relevant levels of uncertainty in the risk assessment process of exposure to airborne NOAA, by comparing PNC measured values with recommended limit values.

Table 2 summarizes a multi-risk approach (both quantitative - with several metrics - and qualitative) followed in the decision-making process on the risk assessment of occupational exposure to nTiO₂ by inhalation, in a case study of the manufacture of a pilot batch of perforated cylindrical tablets (diameter 90 mm) for the steel industry, by cold compressing of nTiO₂ (AEROXIDE® TiO₂ P 25) [9,34].

Task 1 (Weighting TiO₂) and task 2 (Cold compressing TiO₂) were developed in a first MSIS (production hall) where the process evaluated coexisted with other routine manufacturing processes of products for casting, obtained by mixing and compacting metallic powders, among which alloying tablets and mini tablets for the aluminum industry. Task 3 (Drilling tablets) and task 4 (Packaging tablets) were performed in a second MSIS, a maintenance room of dimensions 6x4x3 m without any additional activity except for the referenced tasks.

The quantitative risk assessment approach directly deployed a quantitative Tier 3 strategy [12]. This quantitative approach was combined with a parallel qualitative assessment based on control banding methodology according to ISO 12901-2 [36]. The quantitative strategy was mainly based in the continuous measurement of PNC, corrected with the background aerosol simultaneously measured. The instrumentation deployed for this purpose was an advanced direct-reading instrumentation rack for aerosol source measurement (ELPI +, CPC TSI 3775, among other) and a portable CPC TSI 3007 for background measurement (Figure 3). In addition, personal samples were collected at the workers

breathing zone (BZ) for the off-line analysis of the respirable fraction (SEM, ICP-MS, EDX) (Figure 4).

For the decision-making process and the comparison of exposure measurements with the selected occupational limit values, a NRV of 40,000 particles/cm³ for PNC (8 hours TWA concentration) [13] and a NIOSH OEL of 0.3 mg/m³ for nTiO₂ mass concentration (TWA concentration for up to 10 hours per day) [23], were selected as reference values.

Given the uncertainty about the risk level of exposure to nTiO₂ in the two selected scenarios and to prevent any potential damage to health of monitored workers, during working tasks they were appropriately protected by PPE, such as Tyvek® suit, closed safety glasses, FFP3 filter mask and double nitrile glove.



Figure 3. Rack of DRI located between weighing (right) and cold compressing (left) stations.



Figure 4. Picture taken during a break period in the manufacturing activities, showing a worker carrying two personal samplers (cyclones) for the capture of the aerosol respirable fraction, addressed to off-line analysis (gravimetric, chemical and microscopic).

Quantitative risk approach

Two metrics were used for comparison with limit values: PNC and mass of nTiO₂. In the first case the high background camouflaged any potential NOAA emission and the resulting PNC signals were an indistinguishable combination between background and true NOAA releases. Therefore PNC was not adequate to make a decision on the level of occupational exposure risk.

Using the second quantitative approach [23], although the gravimetry was below the limit of detection (not adequate), the chemical analysis of filters by ICP-MS allowed to determine the airborne concentrations and translate them into exposure values to nTiO₂ weighted in time, for their subsequent comparison with the reference limit value (0.3 mg/m³). The calculated values were between 0.01 and 0.07 mg/m³, representing a SI (Substance Index, EN 689 [37]) in the range <0.1 to 0.2.

These data suggested that the limit value was not exceeded in any of the assumptions evaluated, although according to EN689, additional measurements would be necessary to guarantee the statistical robustness of the results, something in our case was not feasible, since it was a single case study, of limited duration and production, and not of routine operations of the company (exposure scenarios to nTiO₂ were operative for 2 hours).

The SEM analysis of filters provided additional evidence of the presence in the breathing zone (BZ) of nTiO₂ aggregates in the 1-10 µm range. However, the presence of NOAA in the BZ does not justify itself that the exposure limit value has been exceeded.

Qualitative risk approach

The hazard band (HB) selected in all cases is HB = C (Moderate hazard). The exposure band (EB) assigned in all evaluated tasks is EB = 3. Consequently the control band category (CB) to prevent exposure to NOAA is CB = 3 in all cases. According to ISO 12901-2 the decision for risk management control in a proactive manner would be the implementation of enclosed ventilation in the process (ventilated booth, fume hood). In this case, the qualitative approach overestimated the level of risk.

Risk assessment	Qualitative risk assessment			Quantitative risk assessment							
	Control banding (ISO 12901-2)			Comparison with limit values: NRV (2012) and NIOSH (2011)							
	HB	EB	CB	DRI				Off-line analysis			
Working tasks			PNC	NRV #/cm ³	G (1)	ICP-MS (2)	SEM	Exp. 8h mg/m ³	OEL mg/m ³	SI	
1. Weighting TiO ₂	C	3	3	-		-	+	+			
2. Cold pressing TiO ₂	C	3	3	-	40,000	-	+	+	0.01-0.07	0.3	<0.1-0.2
3. Drilling tablets	C	3	3	-		-	+	+			
4. Packaging tablets	C	3	3	-		-	+	+			

(1) NIOSH 0600: All values below the detection limit.

(2) NIOSH 7300 modified (ICP-MS).

Abbreviations: HB=Hazard Band, EB=Exposure Band, CB=Control Band, DRI=Direct Reading Instrumentation, PNC=Particle Number Concentration; NRV=Nano-reference Value (SER 2012), G=Gravimetry, ICP-MS=Inductively Coupled Plasma Mass Spectrometry, SEM=Scanning Electron Microscope, OEL=Occupational Exposure Level (NIOSH 2011), SI=Substance Index, EN 689.

Table 2. Decision-making on the risk assessment of occupational exposure to airborne NOAA (nTiO₂), in a case study of the manufacture of a pilot batch of perforated tablets for the steel industry, by cold compressing of nTiO₂ [(-) Not suitable method, (+) Suitable method].

4. To summarize

With the progressive introduction of ENMs into the industry, exposure scenarios are evolving from well-controlled R&D laboratories and ENMs production plants to industrial processes that incorporate ENMs for the production of intermediate and final NEPs.

Complex exposure scenarios (MSIS) associated with these processes – which will also coexist with conventional non-nanotechnology processes - will be numerous in near future making the assessment of occupational exposure to NOAA more complex and probably expensive for industrial hygienists.

The significant development achieved during recent years in the field of occupational exposure assessment to NOAA (availability of direct-reading instrumentation (DRI) - portable and personal -, tiered approaches, recommended NRVs/OELs), allows a widespread use of new methods and instruments in industrial scenarios. However the complexity of some workplaces highlighted the next step directions in research:

- The determination of the most reliable strategy for the background assessment
- The identification/development of cost effective and chemical selective methods
- The use of DRI as the core block of the engineering controls

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Acknowledgments

This paper exploits the results of the research developed by projects SCAFFOLD and EHS Advance. Project SCAFFOLD received funding from the European Union's FP7 research and innovation programme, under grant agreement No. 280535. This paper reflects only the authors' views and the Commission is not responsible for any use that may be made of the information contained therein. Project EHS Advance received funding from the Basque Government research programme (Etortek). The authors would also like to express their grateful to companies BOSTLAN (Bizkaia, Spain) and TECNAN (Navarra, Spain) for the support provided to carry out the exposure measurements in their respective facilities.